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Abstract. The first demonstration of the grazing incidence pumping (GRIP) scheme for laser-driven x-ray lasers (XRLs) is described utilizing 2-pulse pumping. A long pulse is incident normal to the target to produce a plasma with a particular density profile. Then a short pulse is incident at a grazing angle, chosen to optimally couple the short pulse laser energy into the specific density region where the inversion process will occur. The short pulse is simultaneously absorbed and refracted at a maximum electron density specified by the chosen pump angle then turns back into the gain region. The increased path length gives improved absorption allowing a reduction in the drive energy required for lasing. A Ni-like Mo XRL at 18.9 nm has been demonstrated with only 150 mJ total pump energy and a repetition rate of 10 Hz. We report high gains of 60 cm^{-1} and the achievement of gain saturation for targets of 4 mm length.

1. Introduction

High power, tabletop lasers [1] can be used as a pump source for short wavelength, high repetition rate lasers. A longitudinally pumped, high repetition rate 41.8 nm laser was first reported for a low density Xe gas cell heated by a 40 fs laser using optical field ionisation (OFI) followed by collisional excitation [2]. Transient collisional excitation x-ray lasers were demonstrated where Ne- and Ni-like ion schemes were pumped with ~1 ps laser pulses with less than 10 J of energy and saturated output achieved [3, 4]. Transverse pumping geometry was utilised here where the laser beams were incident at normal incidence and the pump energy was absorbed over a wide range of plasma densities. Further progress in the OFI scheme was reported and the gain saturation regime was achieved for the Pd-like Xe laser at 41.8 nm [5]. This was extended to the shorter wavelength Ni-like Kr at 32.8 nm pumped with energy < 1 J and at a repetition rate of 10 Hz [5]. A longitudinal pumped Ni-like Mo x-ray laser at 18.9 nm was also demonstrated [6], where a short pulse pumps the inversion along a pre-formed plasma column. This laser operated with a pump energy of 150 mJ and produced a highly directional output. High repetition rate and millijoule output 46.9 nm x-ray lasers have also been achieved in the tabletop capillary discharge scheme at 4 Hz and higher [7].

The continuing trend has been to look at ways of improving the efficiency for laser-pumped x-ray lasers operating at shorter wavelengths. We report the first demonstration of a novel pumping scheme using the excitation pulse incident on the plasma column at a grazing incidence angle to create an 18.9 nm Ni-like Mo 4*d* – 4*p* x-ray laser at 10 Hz with a very low energy ~150 mJ laser pump [8].

2. Grazing Incidence Pumping (GRIP) Scheme Description and Results

The GRIP geometry allows improved laser coupling efficiency into a pre-determined optimum gain region of the plasma by using refraction to turn the pump laser at an electron density below the critical density. This increases the path length and absorption in this specific region of the plasma and allows a reduction of the pump energy threshold for inversion. The Ni-like Mo laser was chosen for the initial study of the GRIP scheme using a 100 fs, 800 nm Ti:Sapphire laser at the Lawrence Livermore National Laboratory. A maximum of 300 mJ/pulse uncompressed energy at 10 Hz was split with 33% into a 200 ps long pulse arm and 66% into the short pulse arm. The long pulse energy 70 mJ was focused onto the Mo target at normal incidence in a line of 5 mm long by 15 μm (FWHM), at an intensity of 5×10^{11} W cm^{-2}, see Fig. 1. The short pulse arm was compressed under vacuum where a pulse length of 125 fs to 8 ps could be produced with a maximum of 80 mJ on target. RADEX simulations determined that the turning electron density was determined to be ~10^{20} cm^{-3} from the equation for the refraction angle, ϕ_r, simplified to $\phi_r \sim (n_{eo}/n_{ec})^{1/2}$ where n_{eo} is the maximum density within the gain region and n_{ec} is the critical density for the optical pump [9, 10]. The grazing incidence

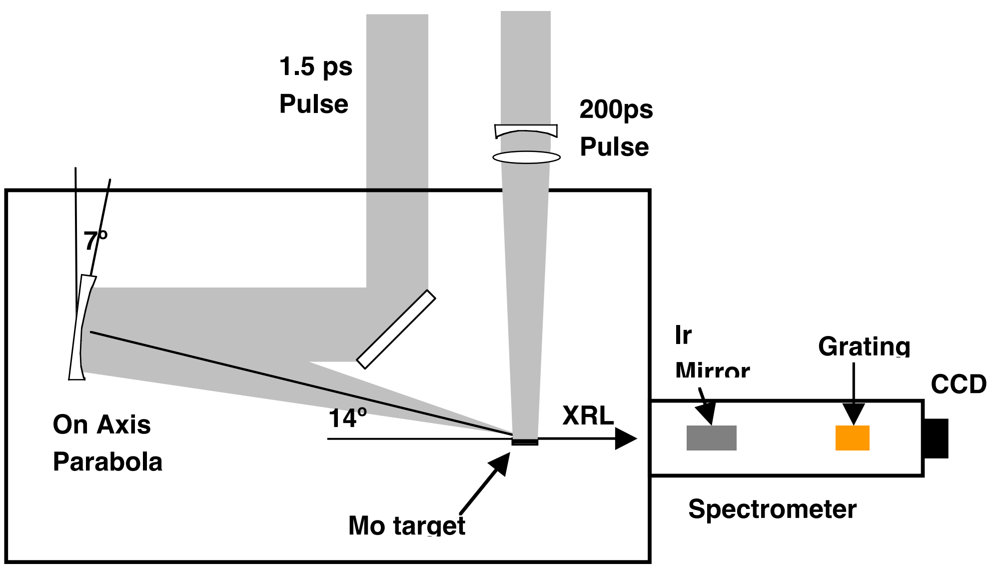

Figure 1 Experimental setup of grazing incidence pumping for Ni-like Mo x-ray laser.

angle for the short pulse beam was determined to be 14° from the critical density of 1.74 $\times 10^{21}$ cm^{-3} for the 800 nm wavelength. An on-axis parabola was used to generate a very uniform line focus 4 mm long by ~25 – 30 μm (FWHM) wide at this angle with an intrinsic travelling wave velocity of 0.97c. A typical short pulse was 1.5 ps at an intensity of 4×10^{13} W cm^{-2}. The long pulse arm was sent through a delay line that could adjust the separation of the two pulses from 0 – 1 ns.

Initially a longer line focus of 8 mm was tried but no lasing was observed in the 18.9 nm line even though Cu-like Mo emission lines were identified in the spectrum [10]. The line focus was reduced to 4 mm which limited the Mo target length to a maximum of 4 mm. Some optimisation of the laser pumping conditions was required to achieve output on the x-ray laser. For the results presented in this paper a 500 ps delay between the laser pulses and a 1.5 ps short pulse duration gave the highest x-ray laser output. More experimental details are reported elsewhere [8, 10]. A spectrum from the on-axis flat-field 1200 l mm^{-1} grating spectrometer with a back-thinned CCD camera is shown in Fig. 2. This is a single shot spectrum from a 4 mm long Mo target pumped by a total of 150 mJ energy. A 1 μm Al foil is used to cut down scattered laser pump light. The x-ray laser line at 18.9 nm is orders of magnitude stronger than any other line. Fiducial wires, observed at 0 and 10 mrad in Fig. 2(b), were placed in front of the spectrometer to determine the angular pointing of the x-ray laser beam. The x-ray laser shows a narrow divergence angle of 3.6 mrad (FWHM) in the horizontal direction with a deflection angle of 3.2 mrad from the target, Fig. 2(b). The most intensely peaked shots had typical average deflection and divergence angles of 3 mrad and 4.5 mrad (FWHM), respectively. RADEX simulations indicate that the measured deflection angles are consistent with optimum electron densities from 4×10^{19} cm^{-3} and up to a maximum of 10^{20} cm^{-3}.

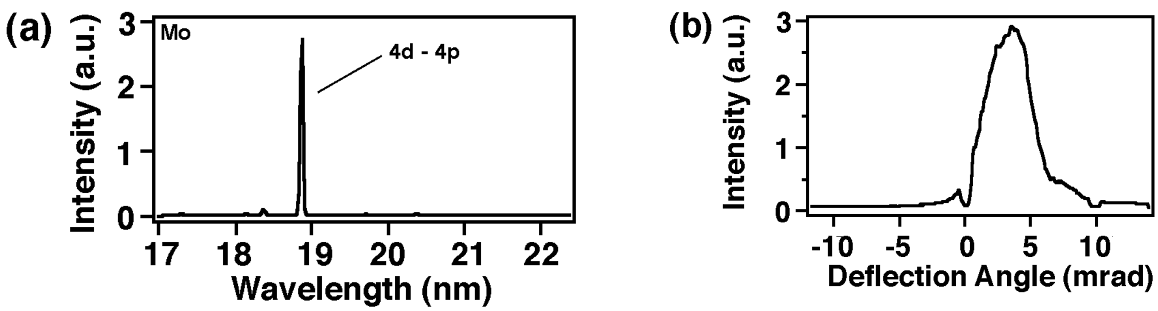

Figure 2(a) Soft x-ray spectrum from on-axis flat-field spectrometer. Strong lasing is observed on Ni-like Mo 4d – 4p transition at 18.9 nm. (b) Horizontal deflection angle showing angular pointing of x-ray laser line. Target axis is 0 mrad and increasing angle is deflected away from the target.

It is noted that if the delay between the two laser pulses was changed by ± 50 ps from the chosen 500 ps then the 18.9 nm intensity dropped substantially. This is understood to be a consequence of the low laser energy and narrow line focus of the 200 ps plasma-forming beam. The GRIP scheme short pulse pumps a specific density region and hence a spatial region of the plasma. This places more constraints on the initial conditions before short pulse pumping than for the transverse scheme where a range of plasma densities are pumped. Subsequent experiments with more energy and a wider line focus for the long pulse have shown a wider “lasing window” as a function of this delay [11].

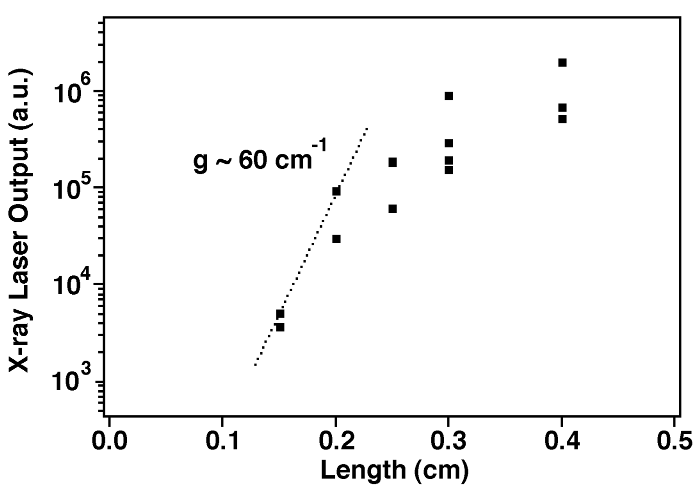

Figure 3 X-ray laser intensity as a function of length for Mo targets up to 4 mm.

Ni-like Mo lasers have shown laser action in recent years to varying degrees with similar small pump energies but with no indication of possible output as a function of length [6, 12, 13]. It was important to determine the gain for the GRIP scheme with travelling wave pumping and scaling of the amplification process with plasma length. The 18.9 nm output of single shots for targets up to 4 mm were recorded using a near-field imaging technique and on the spectrometer, Fig. 3. The XRL intensity increased by approximately three orders of magnitude from the threshold of detection for 1.5 mm targets to the maximum of 4 mm. The highest gain is determined to be 60 cm^{-1} for targets up to 2 mm with no output detected for targets below 1.5 mm. For a 2 mm target the gain length (GL) product of 12 is achieved with the output rolling over indicating a saturation-like behavior. The intensity increases by a further factor of 20 for targets up to 4 mm long which determines an upper limit of GL~15 which would be into saturation.

3. Conclusions

The new grazing incidence pumping scheme has demonstrated x-ray laser action for Ni-like Mo at 18.9 nm with only 150 mJ total pump energy on target operating at 10 Hz. The angle of incidence of the short pulse is chosen to pump the inversion efficiently at a specific density region where the gain occurs. Gain saturation regime has been achieved. We believe this is a major step forward for efficient x-ray lasers that will lead to new applications requiring high average-power x-ray sources at a high repetition rate.

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